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Eversole, John S.; Stuckenbruck, Frederico; Labourian, Ivan G.

Massachusetts Institute of Technology

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SEMI-FLEXIBLE SELF VARYING CAMBER RUDDER

BY
JOHN S. EVERSOLE
FREDERICO O. STUCKENBRUCK
AND
IVAN G. LABOURIAU

Thesis
E8

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Annapolis, Md.

Cambridge, Massachusetts
15 May 1950

Professor J. S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled "Semi-flexible Self Varying Camber Rudder."

Respectfully,

SEMI-FLEXIBLE SELF VARYING CAMBER RUDDER

by

John S. Eversole
Lt. Cmdr., U.S. Navy
B.S. United States Naval Academy
(1939)

and

Frederico O. Stuckenbruck
Lieut., Brazilian Navy
B.S. Brazilian Naval Academy
(1939)

and

Ivan G. Labouriau
Lieut., Brazilian Navy
B.S. Brazilian Naval Academy
(1941)

Submitted in Partial Fulfillment of the
Requirements for the Degree of
NAVAL ENGINEER
at the
Massachusetts Institute of Technology
1950

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NOMENCLATURE

C_L - Lift coefficient (dimensionless)

C_D - Drag coefficient (")

F_L - Lift force, lbs.

F_D - Drag force, lbs.

V - Water velocity, ft/sec.

ρ - Water density

S - Model rudder area (projected)

I. SUMMARY

The object of the work undertaken in preparation of this thesis is the comparison of Lift and Drag Coefficients of an all metal rudder (parent) with those of a family (five) of dimensionally equal rudders which have been modified by cutting away varying percentages of the trailing edge of the parent rudder and replacing the cut away portion with rubber. In order to maintain dimensional equality, six bronze rudders were cast to the same mold, and five were modified as described above. Basic rudder characteristics are: chord - six inches, aspect ratio - one, thickness ratio - 0.19, balance - 20.0%.

Test runs were made in the M.I.T. propeller tunnel at a constant water velocity of 9 feet per second. Lift and drag forces were measured from zero to thirty five degrees angle of attack by means of strain gages mounted in the lower end of a rudder dynamometer. These forces were then converted to dimensionless lift and drag coefficients by dividing the force obtained by the product of: 1/2(water density)x(rudder area) x(water velocity)^2.

The experimental work accomplished shows that, with respect to the all metal rudder (parent), the use of a rubber trailing portion up to about 25% rubber has the effect of increasing the Lift Coefficient, the maximum increase occurring with about 12% rubber and being of the order of 2.8% increase at 30° rudder angle; 7.1% increase at 20°; 10.7% at 10°; and about 25% increase at 5° rudder. Similarly for the Drag Coefficient, a slight increase develops with increase in percentage of rubber up to about

I. [illegible]

The object of the work undertaken in preparation of this thesis is the comparison of Life and Drug Conditions of an all metal rubber [power] with those of a Rubber [type] of approximately equal ratings which have been modified by reducing [the] contact of the trailing edge of the driver web rubber and replacing the [] wedge portion with rubber. In order to maintain dimensional equality, six inserts rubbers were cast in the metal mould, and five were [modified] as described above. Static rubber tension- deflection test showed - six inches, inches equiv = max. deflection ratio = 6.1%, balance - 38.7%.

Two runs were made in the 1.2.7. propeller tunnel at a constant water velocity of 5 feet per second. [A] and drag forces were [measured] three axis to [illegible] the [] edge of [illegible] by means of static gauge mounted in the lower end [illegible]. Three [runs] were then conducted [illegible]. [A] and drag readings by [establishing the force relations] by the product of [illegible] and [power] [illegible].

The experimental work as [illegible] above then, with regard to the all metal rubber [power], the [] a rubber trailing portion by an [illegible] rubber has the effect of increasing the [] flexibility. The [illegible] increases varying [] with about [illegible] rubber and being of the order of [illegible] increase at 30° [rubber] angle [illegible] increases at 60°) 18.7% at 10°) and about 31% increase at 0° radius. [illegible] for the Drag Coefficient, a slight increase [illegible] with increase in [illegible] of rubber up to about

25% rubber, beyond which an increase in percentage of rubber tends to cause the Drag Coefficient to decrease. With 12% rubber the increase in the Drag Coefficient is as follows: 5.5% increase at 30° rudder angle: 6.5% increase at 20°; 13.8% increase at 10°; and 13.3% at 5° rudder angle.

If the ratio of the Lift Coefficient to the Drag Coefficient is to be used as a criterion in judging the relative performance of the rudders, it is noted that the 40% and 50% rubber rudders have considerably higher ratios than the parent rudder.

From the results of the experimental work accomplished, it is concluded that the lift Coefficient is increased, with respect to the parent (all metal rudder), with the use of a rubber trailing edge up to about 25% rubber. Beyond 25% rubber the Lift Coefficient decreases. The Drag Coefficient increases with the addition of rubber up to about 25% rubber and thereafter decreases with the use of more rubber. From a careful study of the results obtained and close observation of the rudders in the tunnel it is concluded that the rubber used was too stiff, in that it did not bend as much as was expected when subjected to the action of the water force.

In view of the results obtained from the experimental work accomplished to date with the rubber-tipped rudders, it is recommended that further experimental work be carried out with them along the following lines:

a) Utilizing rudders with rubber of varying degrees of stiffness.

b) Conducting a close search of the area within which the percentage of rubber varies from 5% to 15%.

c) Performing experiments with all rubber rudders in which the forward part of the rudder is internally stiffened so as to be inflexible for all practical purposes, but a smooth continuous surface is presented to the flow of water around the rudder.

d) Investigating the effects of a ship's hull and propeller upon the behavior of rubber tipped rudders.

c) Experimenting with all rubber cements to avoid the
formed pair of the rubber is temporarily stiffened so as to be no-
ticeable for all practical purposes, but a second application restores
it previous to the time of water stored the rubber.

d) Investigating the effects of a slip's half and overwaller upon the
behavior of rubber tipped fingers.

II. INTRODUCTION

The problem approached in the development of this thesis is the one of providing, for vessels moving through a fluid medium, a control surface which will permit adequate directional control with a minimum of undesirable effects; in the case of a rudder, this means providing maximum lift with minimum drag. The literature cited in Appendix E gives evidence of the extensive research effort directed towards this end.

The use of a rubber tipped rudder, it was thought, would permit the trailing portion of the rudder to fair into the stream of water passing it, to a certain degree, with the result that a small amount of camber would be placed on the rudder. The placement of such camber would be entirely independent of outside mechanical control or adjustment: dependent only upon the forces acting on the rubber and the stiffness of the rubber. The rubber tip would fair downstream: while the force normal to its surface might be smaller than if the surface had not bent, the athwartship component of this normal force, i.e., the lift, would be larger than if acting on a straight surface. By similar reasoning, it was believed that the longitudinal component of the force, i.e., the drag, would be less.

It was decided to experiment on a comparative basis, using one all metal rudder as the basis of comparison; a parent rudder, so to speak. Then five more rudders would be made from the same mold as the parent rudder but with 10%, 20%, 30%, 40%, and 50% of the rudder surface replaced with rubber. The rubber of all rudders was to be cut from the same sheet, to insure that the same rubber characteristics were present

II. DISCUSSION

on all rubber-tipped rudders.

An order for the manufacture of the six rudders was placed with the Boston Naval Shipyard and in due time all six rudders were manufactured. The metal portion was "Composition G Bronze" and the rubber was cut from a sheet of gasket material and cemented to the metal with deck tread cement. While the job order called for a rubber percentage of 10%, 20%, 30%, 40%, and 50%, it was found upon careful measurement that, due to manufacturing errors, the actual percentages of exposed rubber, as measured along the side of the rudders, were as follows:

ORDERED	RECEIVED
0%	0%
10%	15.4%
20%	25.0%
30%	33.5%
40%	40.7%
50%	48.7%

Throughout this thesis the rudders are referred to as 10%, 20%, 30%, 40%, and 50% rubber. It should be borne in mind that the actual percentages are as listed above, under the RECEIVED column.

The actual rudder dimensions are as shown in Figure XI.

Due to the necessity of hand finishing the rubber portion of the rudders, there were slight differences found between rudders, but not of such an extent as to invalidate the comparative results obtained from the experiments. It is worthy of note, however, that due to the construction of the joint between the metal and the rubber, a continuous smooth surface for presentation to the flow of water was not attained, with possible attendant effect on drag components.

The forces acting on the rudder were to be measured by the dynamometer developed and built by Kissinger & Rupp, and described in Appendix A.

The rubber swim fins used by swimmers in gaining ahead thrust, and the shape of racing shell oars used to gain "negative drag" were factors given consideration in the development of the idea of semi-flexible rudders. This same idea was also strengthened by some of the facts found in Nature, such as the extreme mobility of fish tails and the softer feather tips in the trailing edge of birds' wings.

III. PROCEDURE

The first step to be accomplished in the experimental work was accurate calibration of the rudder dynamometer. This was performed by placing the dynamometer in a test rack outside the tunnel and by applying known forces to the rudder stock in a direction which would be parallel to the flow of water, with the dynamometer in the tunnel, and in a direction perpendicular thereto. Calibration curves were then prepared as in Figure III. With the rudder in the tunnel, strain gage readings of deflections in micro-inches were then easily converted to pounds force.

Water speed to be used throughout the experiment was set at 9 ft/sec. in order to stay well within the forces used in the calibration of the dynamometer. During the running of the tests, the water speed was kept under constant monitoring to insure that it was maintained at exactly 9 ft/sec., which corresponds to a Reynolds number of 371,600 (for fresh water at 60°F).

Due to the construction of the dynamometer, the range of rudder angle that could be applied was from 10 degrees left rudder to 36 degrees right rudder.

A "run" consisted of measuring lift and drag forces every few degrees: 3, 5, 7, 10, 13, 15, 17, etc., over the full range of the dynamometer. The location of "zero rudder" was determined by the point at which the Lift Force curve of the run being made crossed the zero axis, going from positive to negative. The Lift and Drag Forces were converted

to dimensionless coefficients as defined in hydromechanics literature:

$$C_L = \frac{F_L}{1/2\ \rho\ S\ V^2} \qquad C_D = \frac{F_D}{1/2\ \rho\ S\ V^2}$$

Three complete runs for all rudders were made, with three additional runs made on the parent all metal rudder in order to insure that the basis for comparison of the remaining family of rudders was sound and accurate. Numerous checks of various points on the Lift and Drag curves were made to insure that consistent results were being obtained.

The calibration of the dynamometer was checked repeatedly during the course of the experimental work.

Upon the completion of the experimental work, the results were plotted in the form of curves of rudder angle vs. Lift and Drag Coefficients for all six rudders and of the following cross curves:

Lift Coefficient vs. Percent Rubber

Drag coefficient vs. Percent Rubber

Lift Coefficient/Drag Coefficient vs. Rudder Angle

$$C_L = \frac{2}{M^2 \cdot 9.81} \qquad C_D = \frac{C_D}{M^2 \cdot 9.81}$$

These equations from lay ed readers were usual. will serve advantage
from inside as the current all metal radius is under to leave that for lasts
her conservation of the resulting density of oxidants rose visual use accurate.
Reduction checks of various points on the Lift-and Drag curves were made
to insure that visualized results were being obtained.

The evaluation of the dynamometer was directly proportional during the
course of the experimental work.

Upon the completion of the experimental work, the results were plotted
in the form of curves of radius angle vs. Lift and Drag Coefficients for all
six models used of the following curve curves:

Lift Coefficient vs. Forward Inches

Drag coefficient vs. Forward Inches

Lift Coefficient/Drag Coefficient vs. Inches - Angle

IV. RESULTS

The results of the experimental work involved in this thesis are shown in the curves on Figures I to X, inclusive. The only variable quantities entering into the results are the percentage of rubber on each rudder and the water density. The water density was corrected for temperature throughout. The velocity of the water was kept constant at 9 ft/sec. The area of all rudders is taken as 36 square inches, i.e., projected area (12).

Observation of the experimental runs in progress showed that the rubber did not flex nearly as much as was anticipated, indicating that the rubber used was too stiff. With 50% rubber a slight but definite deflection was noticed.

A galvanometer was used to indicate balance in the SR-4 Strain Gage Indicator, in measuring forces on the rudder. It was anticipated that with the rubber tips on the rudders there would be a considerable amount of flutter or vibration, which would show on the galvanometer, probably making it difficult to balance. This, however, was not the case. In measuring lift, the amount of vibration appeared to be about the same for both the solid and rubber-tipped rudders. In measuring drag, it was found that the rubber-tipped rudders gave remarkably more steady readings than were given by the all metal rudder.

Figures I to VI are individual plots for each rudder. Figures VII to X give comparative results among the rudders in the form of cross-curves and multiple plots.

[illegible] in the curves on Figures 1 to 4, inclusive. The only exception [illegible] water velocity. The water velocity was measured for [illegible] The velocity of the water was kept constant at 9 ft/sec. [illegible] results is taken as 12 square inches, i.e., [illegible] (12).

Observation of the experimental runs on Pitchford showed that the rubber did not flow nearly as much as it was anticipated, indicating that the rubber used was too stiff. With more rubber a slight [illegible] was noticed.

A phenomenon was noted in testing [illegible] Battelle. On inspecting [illegible] the rubber type on the rudder there would be a [illegible] Under or vibration, which would show on the [illegible] a cessation to balance. This, however, was not the case. In [illegible] the amount of vibration [illegible] rubber-stopped rudders. In [illegible] tipped rudders were considerably [illegible] the all round rudder.

Figure 1 to 11 are individual plots for each rudder. Figure 12 is a [illegible] comparative results showing the rudders in the form of [illegible] and multiple plots.

FIGURE I

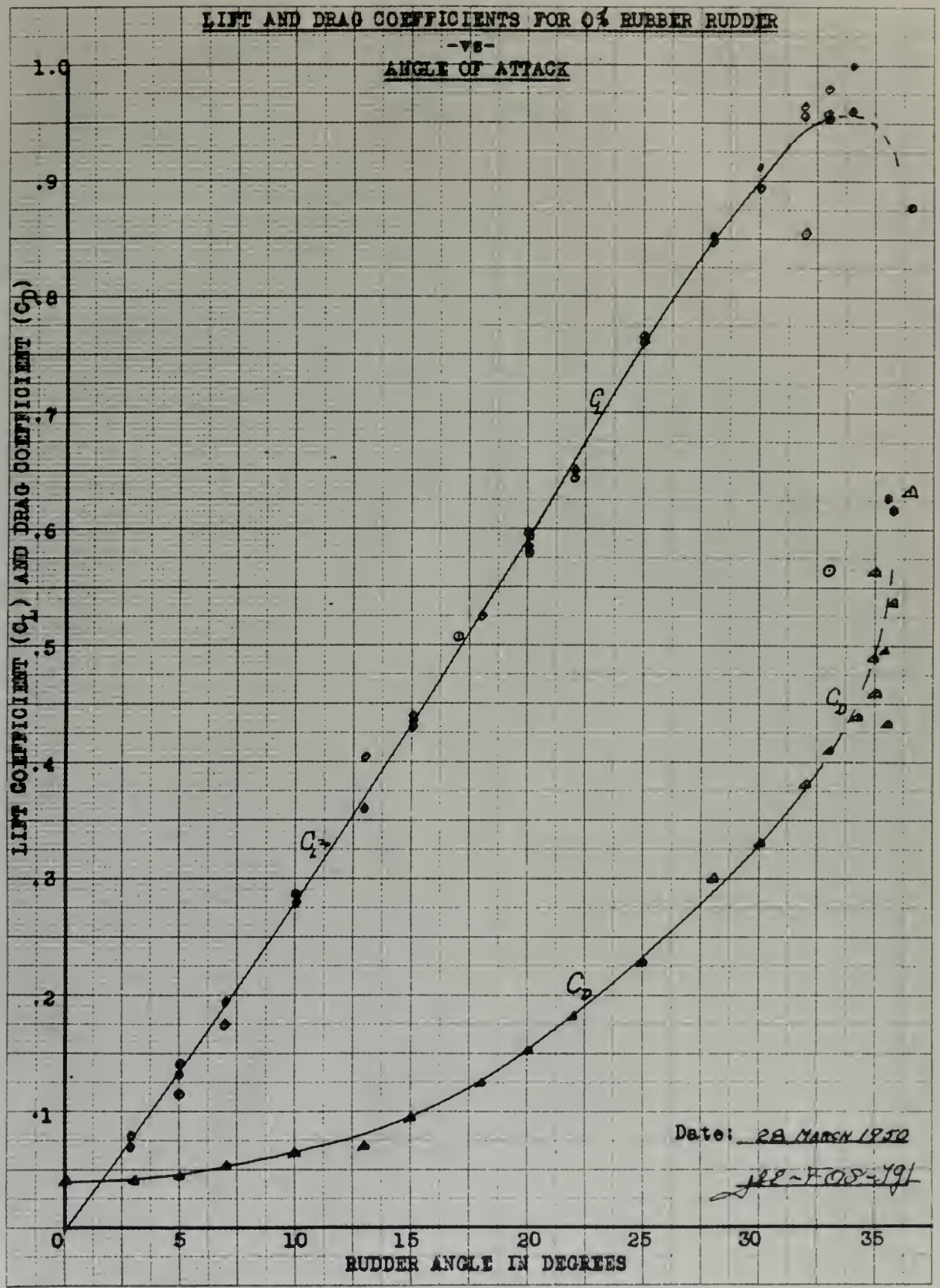

LIFT AND DRAG COEFFICIENTS FOR 0% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
C_L
C_D
C_L
C_D
Date: 28 March 1950
NAE-FOS-191

FIGURE II

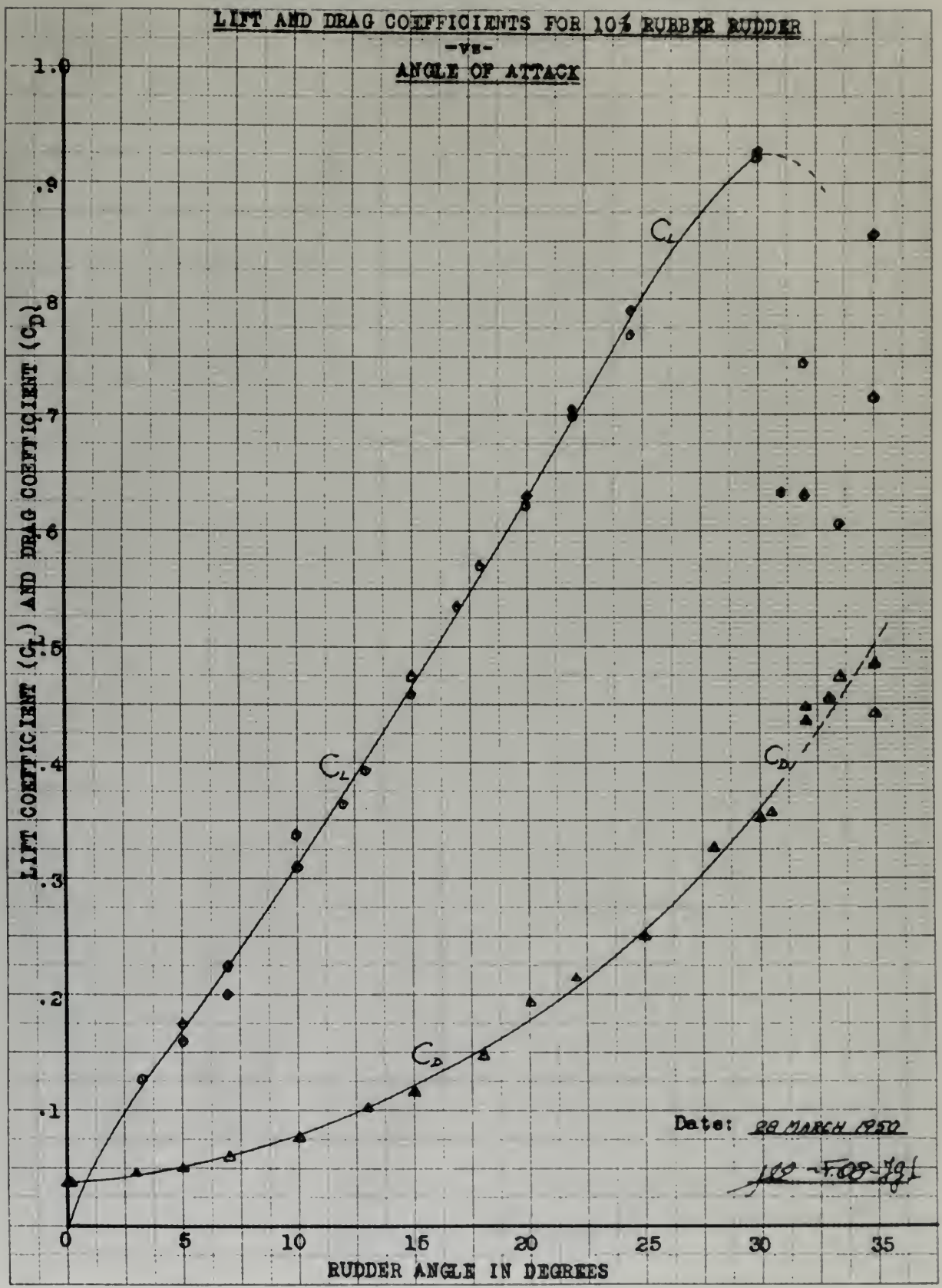

LIFT AND DRAG COEFFICIENTS FOR 10% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
C_L
C_L
C_D
C_D
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
Date: 28 MARCH 1950
100-F.08-191

FIGURE III

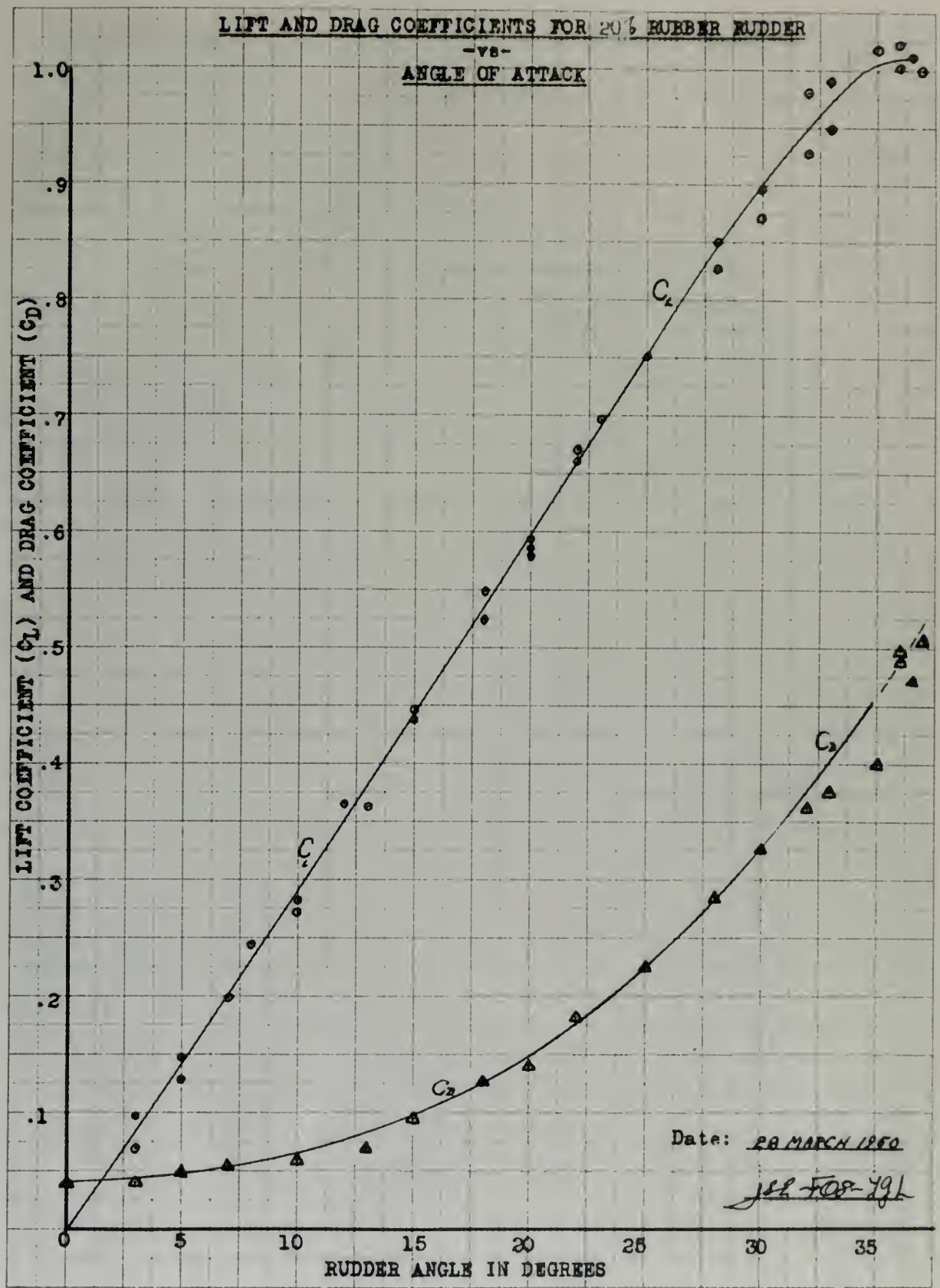

LIFT AND DRAG COEFFICIENTS FOR 20% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
C_L
C_D
C_1
C_2
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
Date: 28 MARCH 1950
JSL FOR-791

FIGURE IV

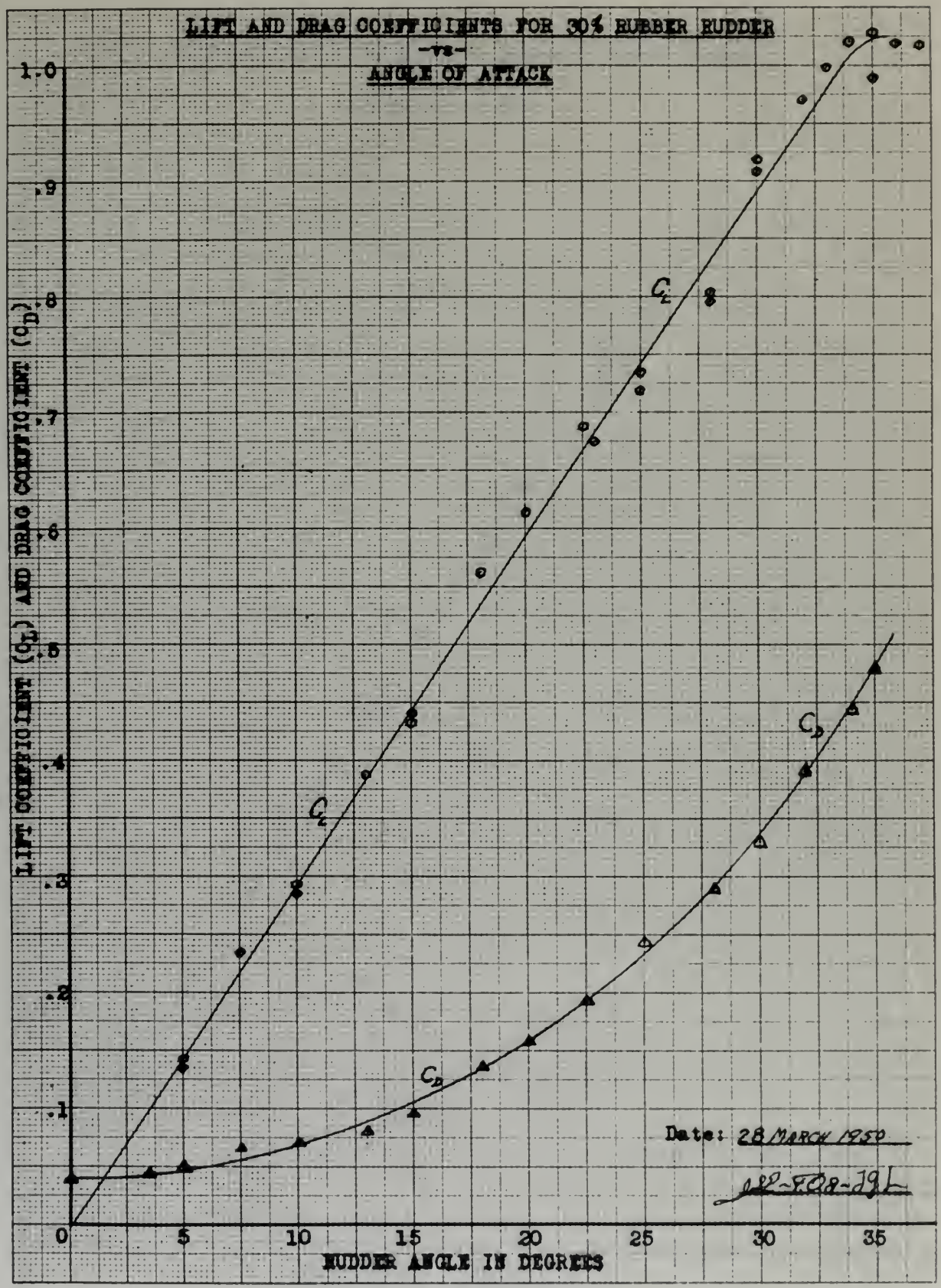

LIFT AND DRAG COEFFICIENTS FOR 30% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
C_L
C_D
Date: 28 MARCH 1950
NP-FOR-JJL

FIGURE V

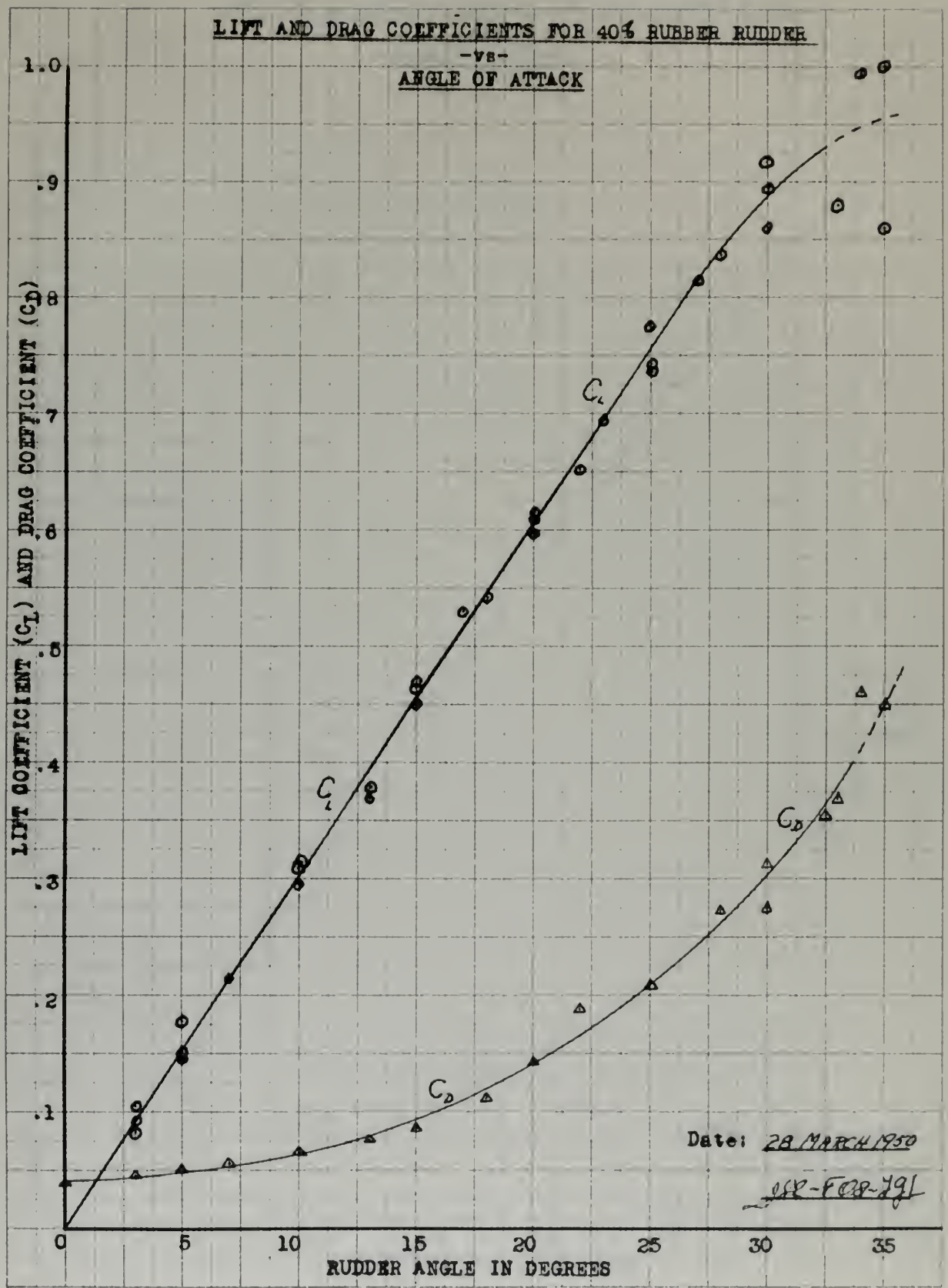

LIFT AND DRAG COEFFICIENTS FOR 40% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
C_L
C_L
C_D
C_D
Date: 28 MARCH 1950
USE-FOR-791
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES

FIGURE VI

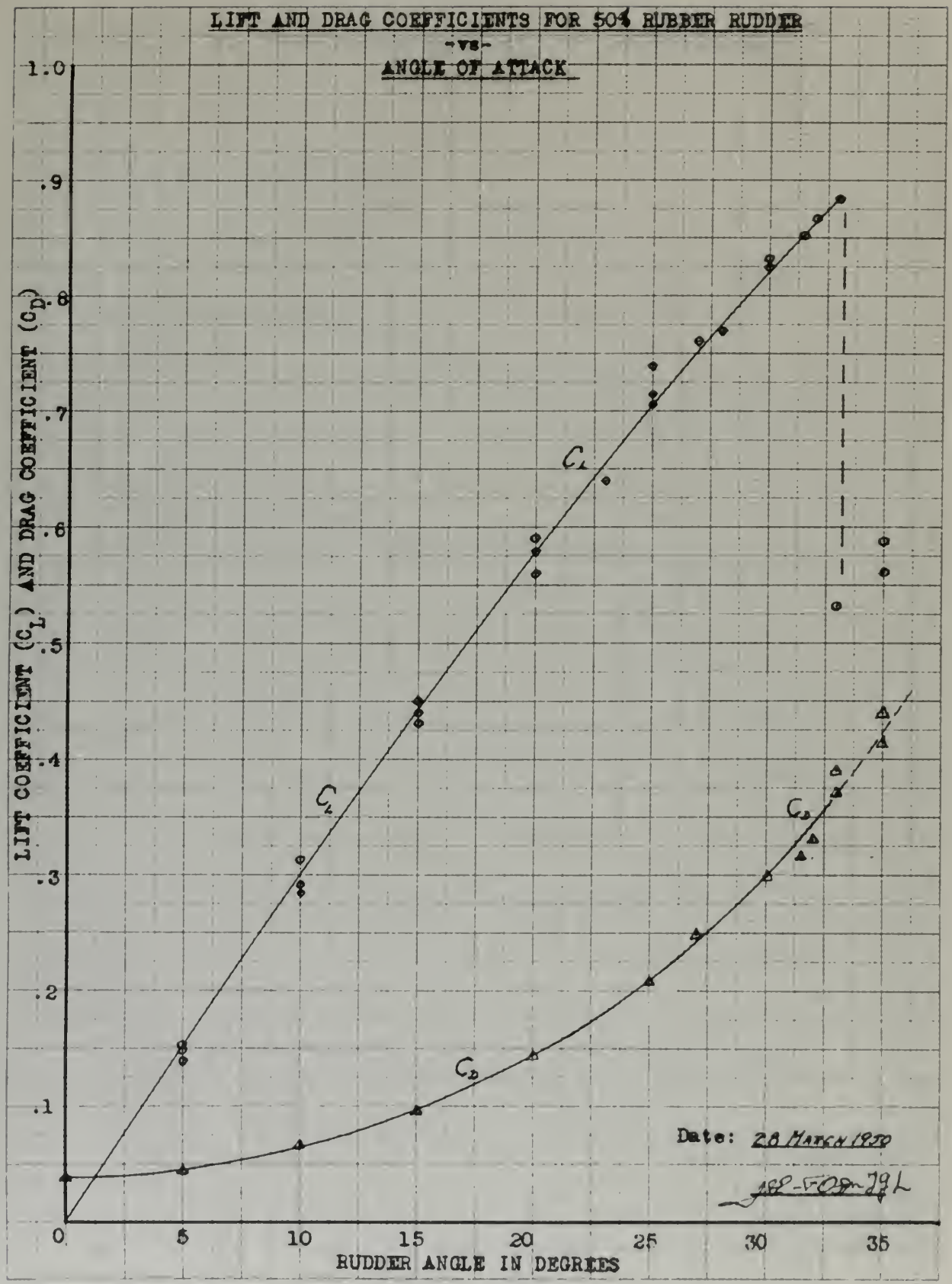

LIFT AND DRAG COEFFICIENTS FOR 50% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
C_L
C_D
C_L
C_D
Date: 28 March 1939

FIGURE VII

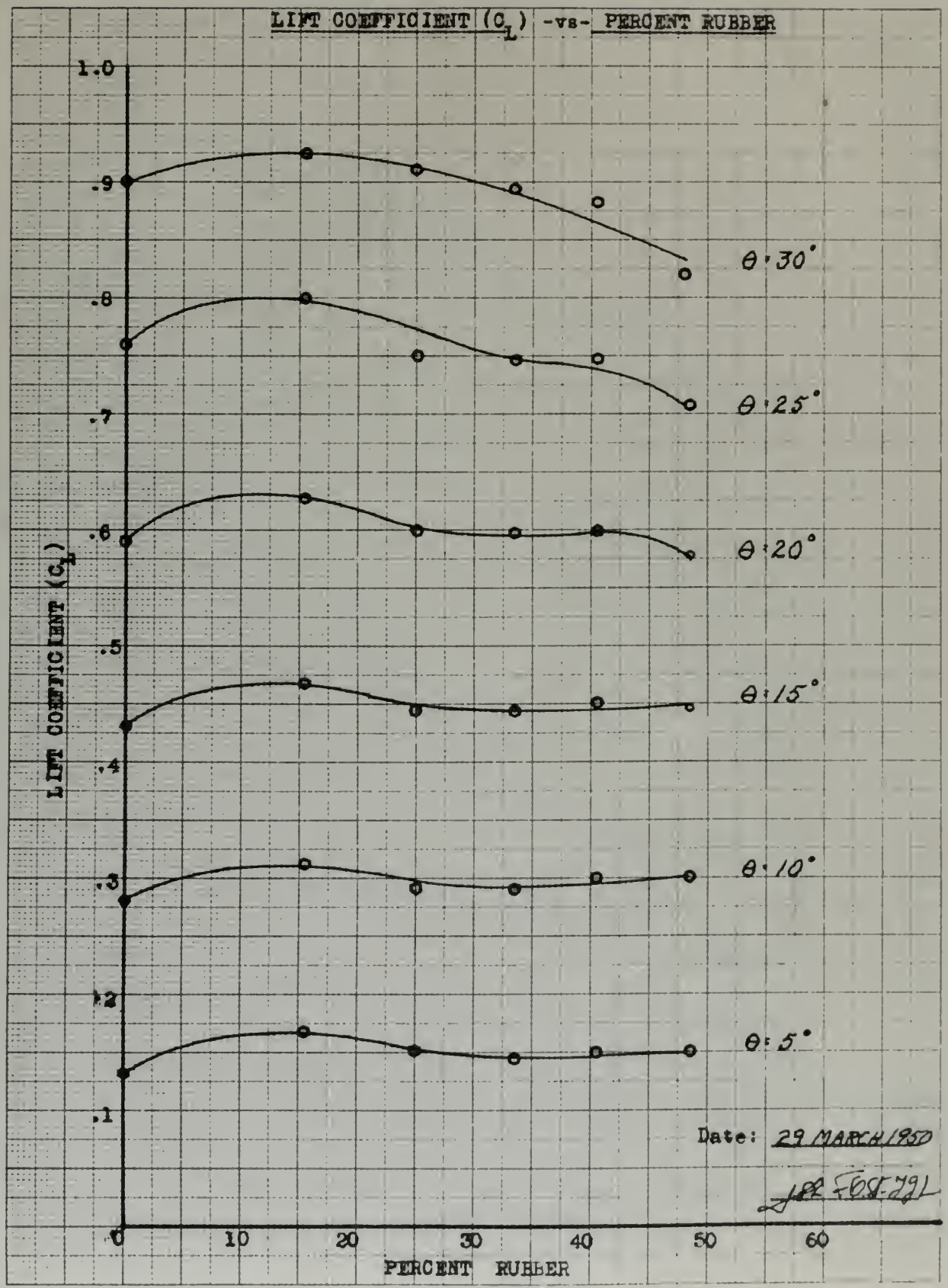
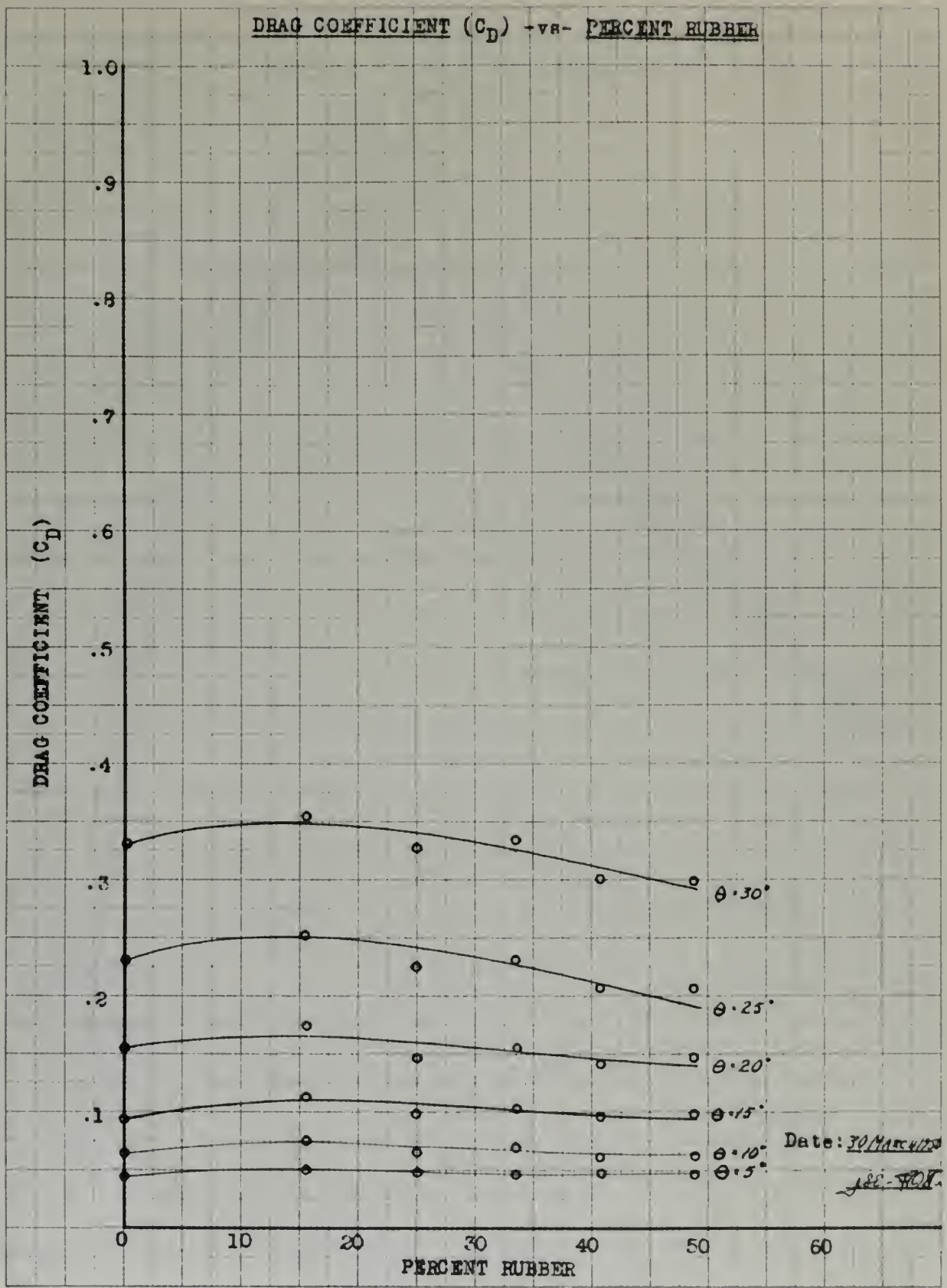

LIFT COEFFICIENT (C_L) -vs- PERCENT RUBBER
LIFT COEFFICIENT (C_L)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
10
20
30
40
50
60
PERCENT RUBBER
θ = 30°
θ = 25°
θ = 20°
θ = 15°
θ = 10°
θ = 5°
Date: 29 MARCH 1950
LRC F08-291

FIGURE VIII


DRAG COEFFICIENT (C_D) -vs- PERCENT RUBBER
DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
10
20
30
40
50
60
PERCENT RUBBER
θ·30°
θ·25°
θ·20°
θ·15°
θ·10°
θ·5°
Date: 30 March 1955

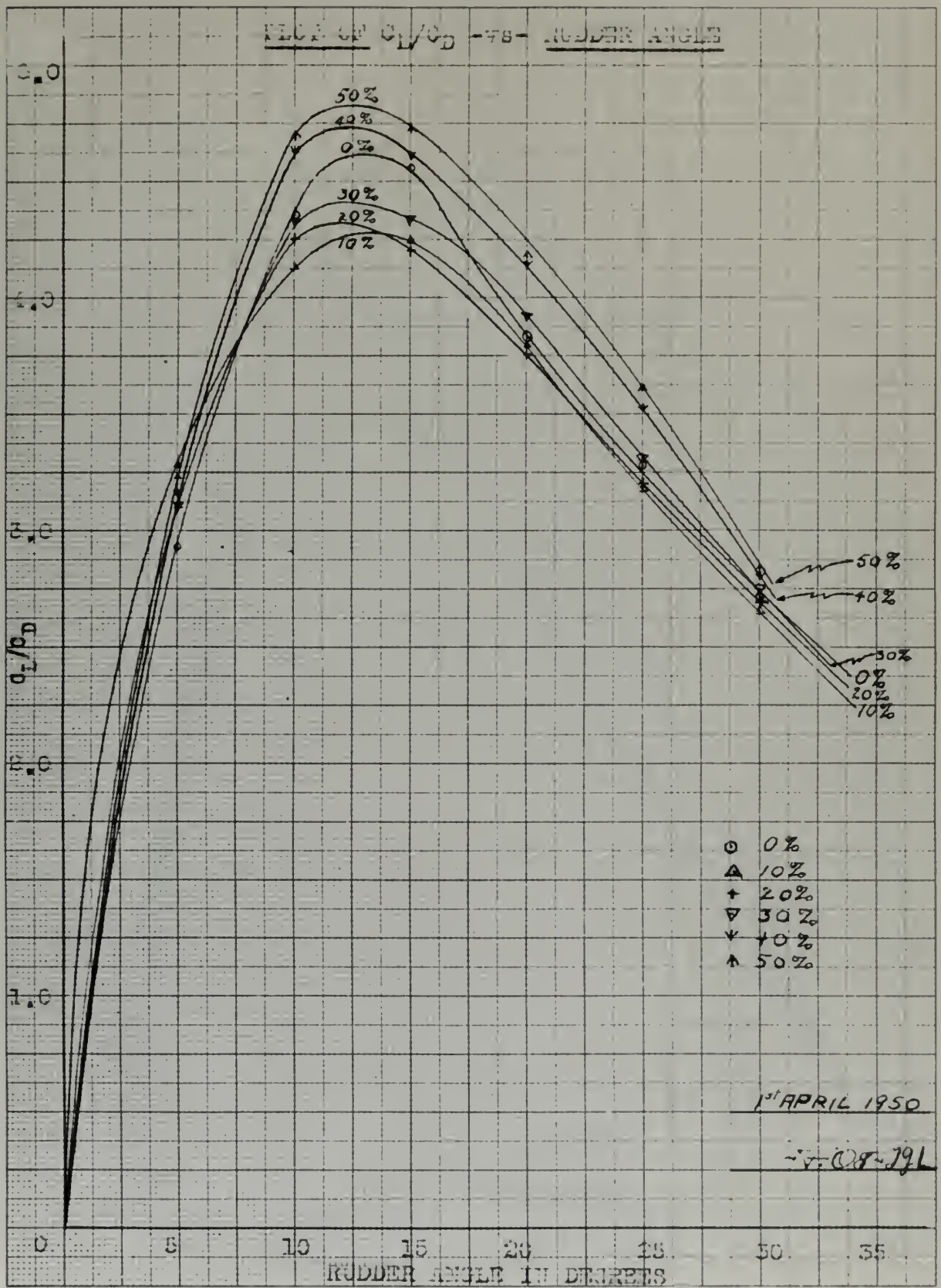
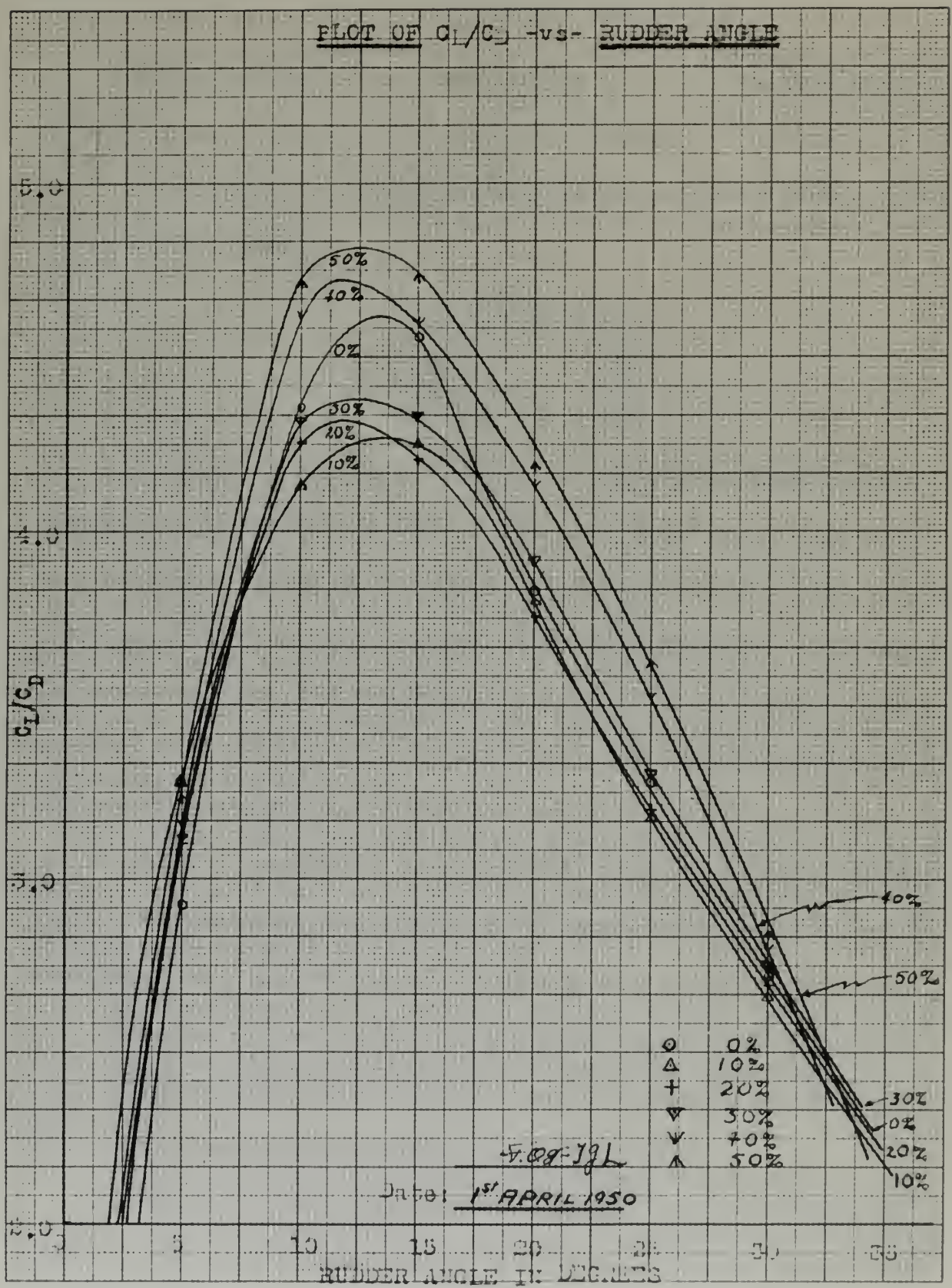

PLOT OF C_L/C_D -VS- RUDDER ANGLE
C_L/C_D
RUDDER ANGLE IN DEGREES
0
5
10
15
20
25
30
35
50%
40%
0%
30%
20%
10%
0% 10% 20% 30% 40% 50%
1st APRIL 1950

FIGURE X


PLOT OF C_L/C_D -vs- RUDDER ANGLE
C_L/C_D
RUDDER ANGLE IN DEGREES
50%
40%
0%
30%
20%
10%
0 0%
Δ 10%
+ 20%
▽ 30%
▼ 40%
▲ 50%
F.O.B. - J.J.L.
Date: 1st APRIL 1950

V. DISCUSSION OF RESULTS

The intention of the experiment was to determine the characteristics of rudders with 10%, 20%, 30%, 40%, and 50% rubber. However, the rudders as received from the Boston Naval Shipyard and as tested, had the following percentages of rubber:

15.4%	in	lieu	of	10%
25.0%	"	"	"	20%
33.5%	"	"	"	30%
40.7%	"	"	"	40%
48.7%	"	"	"	50%

There are several possible sources of error in the experimental results obtained which it is well to recognize at this time. First, while the rubber tips used on all rudders were cut from the same sheet of rubber, in an attempt to have rubber with the same characteristics on all rudders, the necessary fitting and machining of the rubber in the process of manufacturing the finished product did introduce some small differences among rubber tips. Secondly, the method of attachment of the rubber to the metal was of such a nature that the drag coefficient might be increased due to the break at the juncture (see the 50% rubber rudder of Figure 18). Thirdly, the rubber tip on the 10% rudder seems to be of a rougher surface than any of the other rubber tips, all of which had the same feel to the hand. This slightly rougher rubber surface, on the 10% rudder, may account in part for the increased drag observed with this rudder.

The rudders were balanced about the rudder stock by drilling out metal aft of the stock until a hanging balance was obtained. These holes were closed with putty prior to running tests in the tunnel, hence insuring

7. DISCUSSION OF RESULTS

The intention of the experiment was to determine the characteristics of rubbers with 10%, 30%, 40%, and 60% rubber. However, the rubbers as received from the Lawton Rubber Company and as tested, had the following percentages of rubber:

13.4%	in lieu of 10%
25.0%	" " " 30%
31.6%	" " " 40%
48.7%	" " " 60%
64.3%	" " " 80%

There are several possible sources of error in the experimental results obtained which it is well to recognize at this time. First, while the rubber tips used on all rubbers were cut from the same sheet of rubber, in an attempt to have rubber with the same characteristics on all rubbers, the necessary filing and machining of the rubber in the process of mounting the finished product did introduce some small differences among rubber tips. Secondly, the method of attachment of the rubber to the metal was of such a nature that the drag coefficient might be increased due to the break at the junction (see the 30% rubber rubber at figure 18 b. Thirdly, the rubber tip on the 10% rubber seems to be of a rougher surface than any of the other rubber tips, all of which had the same level in the final. This slightly rougher rubber surface, on the 10% rubber, may account in part for the increased drag observed with this rubber.

The rubbers were retained about the rudder stock by drilling and dowel pin at the stock until a tapering tapper was obtained. These holes were closed with putty prior to inserting stock in the rudder, hence increasing

a smooth surface.

The metal portion of all rudders should be very nearly identical, as all were cast to the same mold. No discrepancies among the metal portions of the family of rudders was discernible.

No sources of error, other than the ever present human element, are known at this time, to exist.

From a study of figures I and VI, and observation of the tests as they were conducted, rudder breakdown seems to occur as follows:

RUDDER	RUDDER ANGLE AT BREAKDOWN
0%	30°
10%	30°
20%	32°
30%	35°
40%	32°
50%	33°

From these figures it would appear that the addition of rubber does not hasten the arrival at the breakdown angle and does have the effect of delaying this angle a few degrees.

Figure VII shows that Lift is increased by the use of rubber up to about 25% rubber at all angles of attack, but that with more than 25% of rubber the Lift falls off at angles of attack above 15°.

From Figure VIII it is seen that Drag increases with the use of rubber up to about 25% rubber and that with more than 25% rubber, the Drag decreases.

In Figures I-VI the location of 0° angle of attack was determined by measuring Lift from right rudder to left rudder and plotting the Lift against the angle of attack as indicated on the dynamometer movable head. This

a smooth surface.

The metal portion of all rudders should be very nearly identical, as all were cast in the same mold. The discrepancies among the metal portions of the family of rudders was discernible.

No sources of error, other than the ones previously mentioned, are known at this time, to exist.

From a study of figures I and VI, and observation of the tests as they were conducted, rudder breakdown seems to occur as follows:

[illegible]	[illegible] AT BREAKDOWN
0°	30°
10°	40°
20°	50°
30°	30°
40°	25°
50°	25°

From these figures it would appear that the addition of rubber does not lessen the available angle and does save the effect of decreasing this angle a few degrees.

Figure VII shows that lift is increased by the use of rubber up to about 25° rubber at all angles of attack. But that with more than 25° of rubber the lift falls off at angles of attack above 10°.

From Figure VIII D is seen that drag increases with the use of rubber up to about 25° rubber and then with more than 25° rubber, the drag decreases.

In Figure I-VI the location of 0° angle of attack was determined by measuring lift from right rudder to left rudder and plotting the lift against the angle of attack as indicated on the dynamometer scale used. This

plot was very nearly a straight line and 0° angle of attack was set at the point where the plotted line crossed (zero lift) the coordinate axis showing rudder angle in degrees.

In order to produce comparative results, the drag for zero angle of attack for all rudders was corrected to the drag of the all metal rudder at zero angle of attack. For each rudder, this very small correction was applied to all values of the Drag Coefficient, thence the curves were plotted.

Beyond the point at which the rudder was believed to have reached breakdown, the Coefficient curves are dotted in, as the exact behavior of the rudder beyond this point was indeterminate.

The model Rudder Dynamometer would not give readings above 36 degrees right rudder and 10 degrees left rudder.

VI. CONCLUSIONS

1. With respect to the all metal rudder, the use of rubber in the construction of the rudders increased the Lift Coefficient, the maximum increase being obtained with about 12 1/2% rubber. Beyond about 25% rubber the Lift Coefficient decreases.
2. The Drag Coefficient increases up to about 25% rubber, decreasing with increase of rubber beyond 25%.
3. With respect to the all metal rudder the C_L/C_D ratio is larger for all rubber-tipped rudders at small angles of attack, below about 8°. This ratio is larger for the 40% rubber rudder at all angles of attack.
4. The rubber used in the experiment was too stiff for best performance.

1. With respect to the A5 normal rubber, dry set of rubber in the specifications of the rubbers increased the L/A Condition, the specimens increase being elongated with below 11 L/A rubbers. Increased above A5% rubber the L/A Condition decreases.

2. The Drug Conditions Increases up to about 17% rubber, decreasing with Increase of rubber beyond 17%.

3. Oils compare to the A5 normal rubber the Cr/Cl ratio is larger for all rubber-dipped products at same region of strain, below about 5%. Then ratio is larger for the A5% rubber. Rubber at A5 origins is normal.

4. The rubber used in the experiments was not oil in over-vulcanized.

VII. RECOMMENDATIONS

1. That further experimental work be done with semi-flexible rubbers along the following lines:

    a) Utilize rubber of varying degrees of stiffness.

    b) Conduct a close search of the area within the 5% to 15% rubber zone.

    c) Conduct experiments with all rubber rudders in which the forward portion (percentage determined by previous work), of the rudder is stiffened by internal framework so that it is inflexible and the after portion free to flex. Use of such a rudder would exclude the possibility of erroneous results such as increased drag due to the break at the junction of the rubber and metal.

2. That the possibility of using a flexible trailing edge on propellors be investigated.

3. That the effects of the ship's hull and the propellers race on the rubber-tipped rudders be investigated.

VII. RECOMMENDATIONS

1. That further experimental work be done with cross-flowable rubbers along the following lines:

   a) Testing under of varying degrees of stiffness.

   b) Checking to close control of the cure within the 37° to 100°F temperature range.

   c) Checking superficially with all rubber varieties to attain the necessary qualities (previously determined by synthetic tests), as the rubber is subjected to identical treatment so that it is determine just the other possible flow to them. Any of such a rubber would continue the possibility of extensive testing such as determined flow rate to the break at the junction of the rubber and metal.

2. That the possibility of using a flexible bonding edge be investigated.

3. That the effects of the ship's hull and the propellers cause on the rubber-lipped rudders be investigated.

FIGURE XI

MODEL RUDDERS

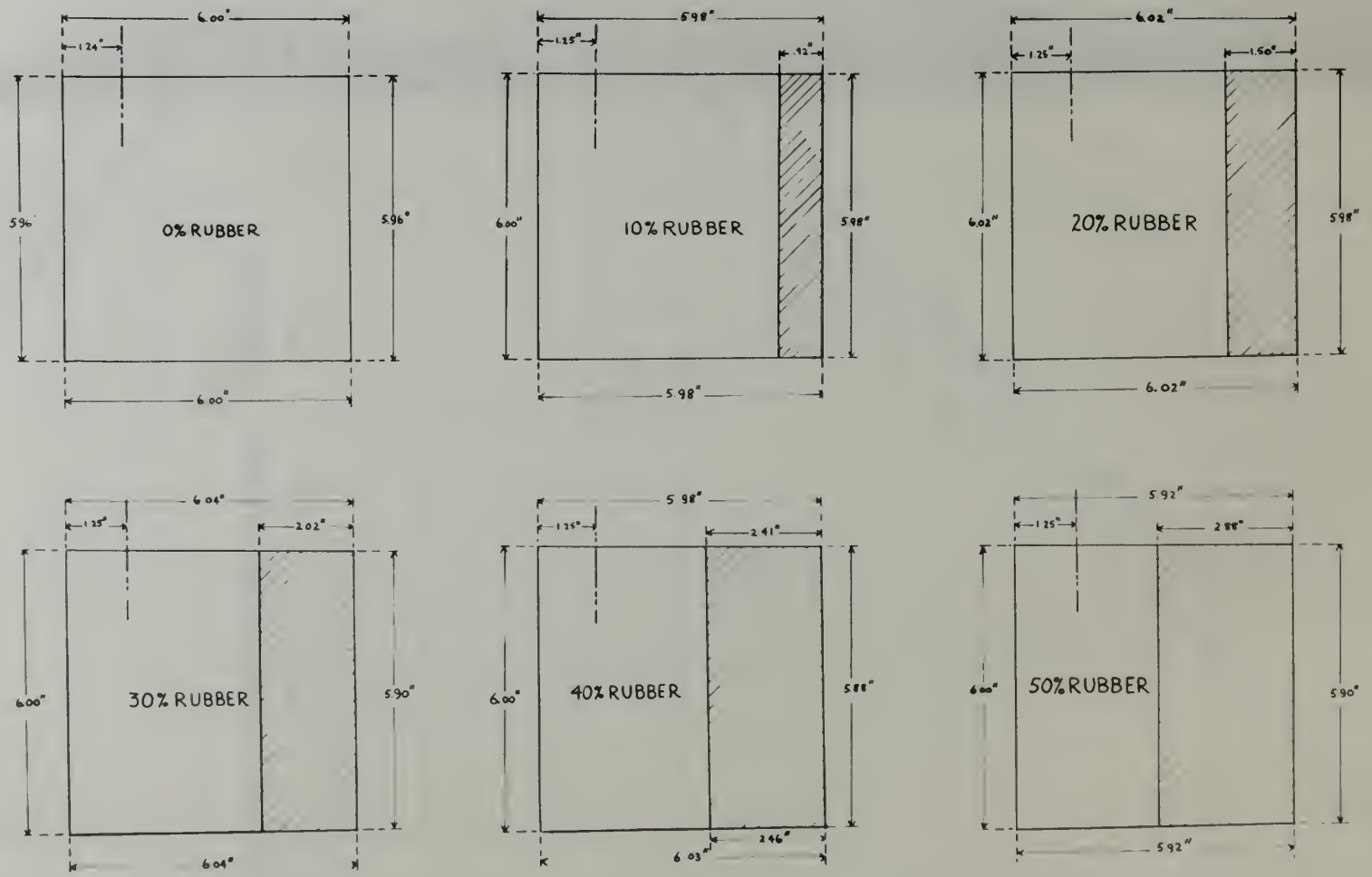


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FIGURE XII

CALIBRATION CURVES FOR RUDDER DYNAMOMETER

APPLIED LOADS VS INSTRUMENT READINGS

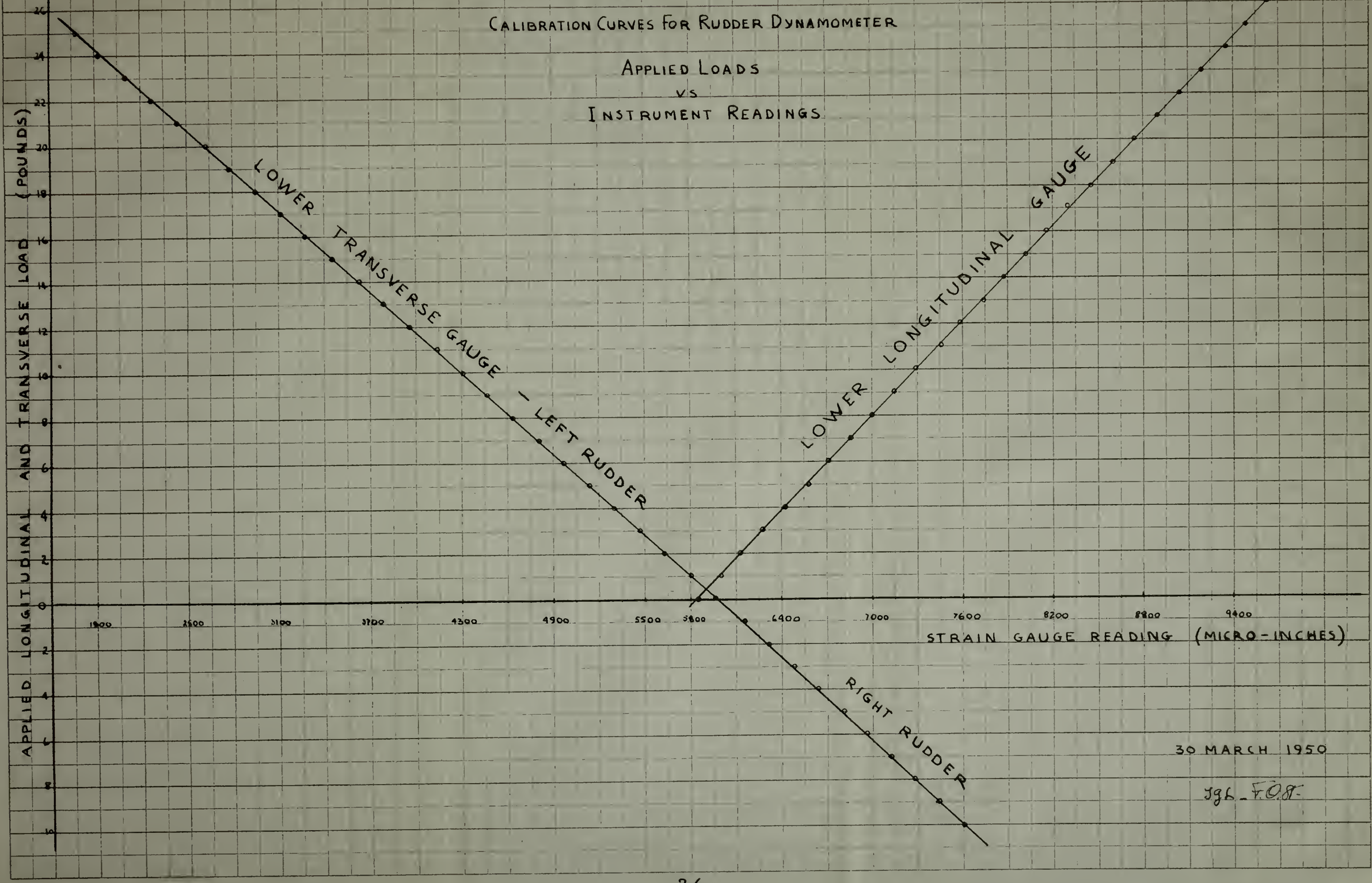

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FIG. XIII - INSTRUMENTS

FIG XIV- INSTRUMENTS AND DYNAMOMETER

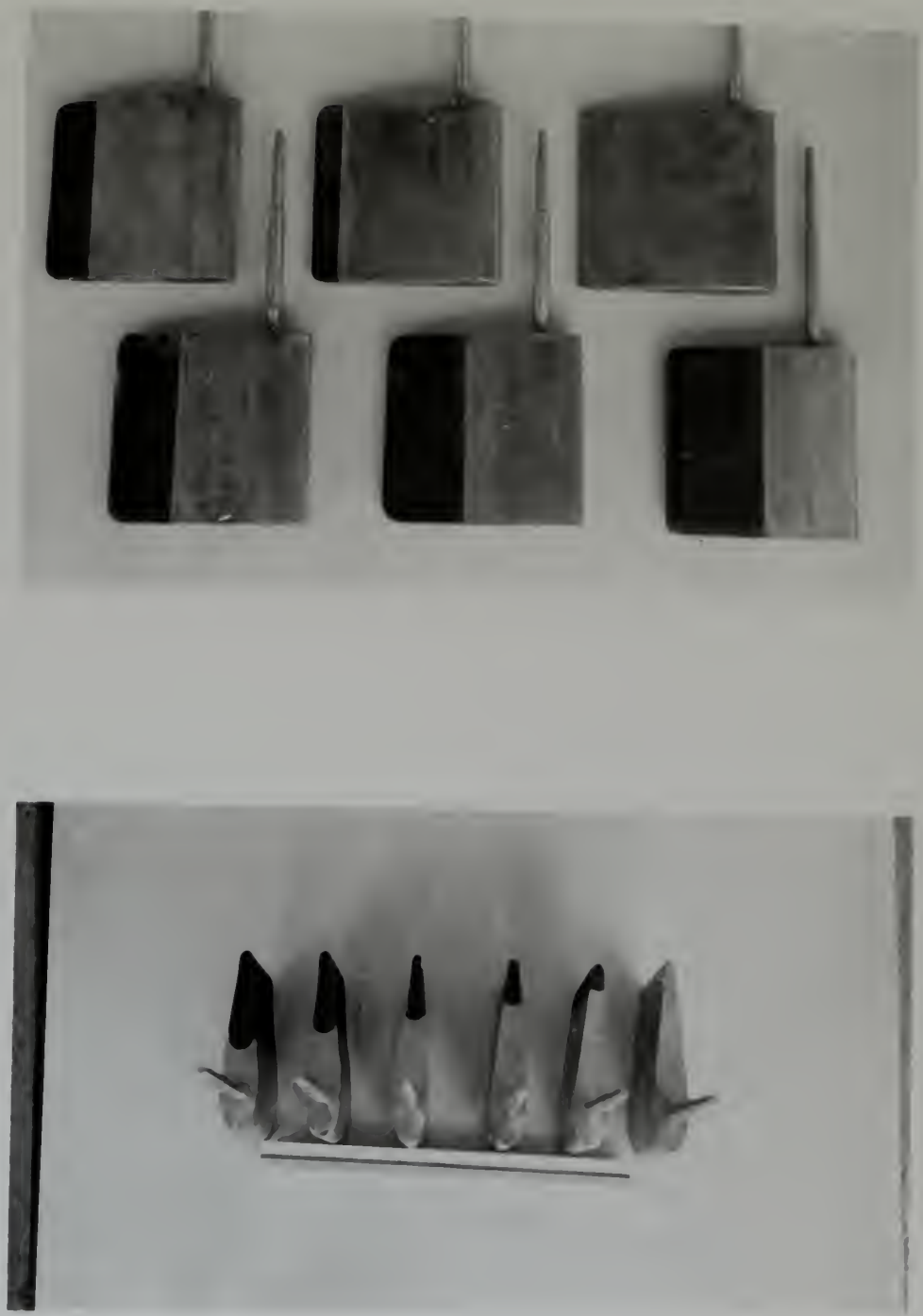


FIG XV — MODEL RUDDERS

FIG XVI – ELEVATION AND PLAN VIEW OF MODEL RUDDERS

FIG XVII— 40% RUBBER RUDDER

FIG XVIII - RUDDER BEING BENT

FIG XIX – CALIBRATION SET-UP

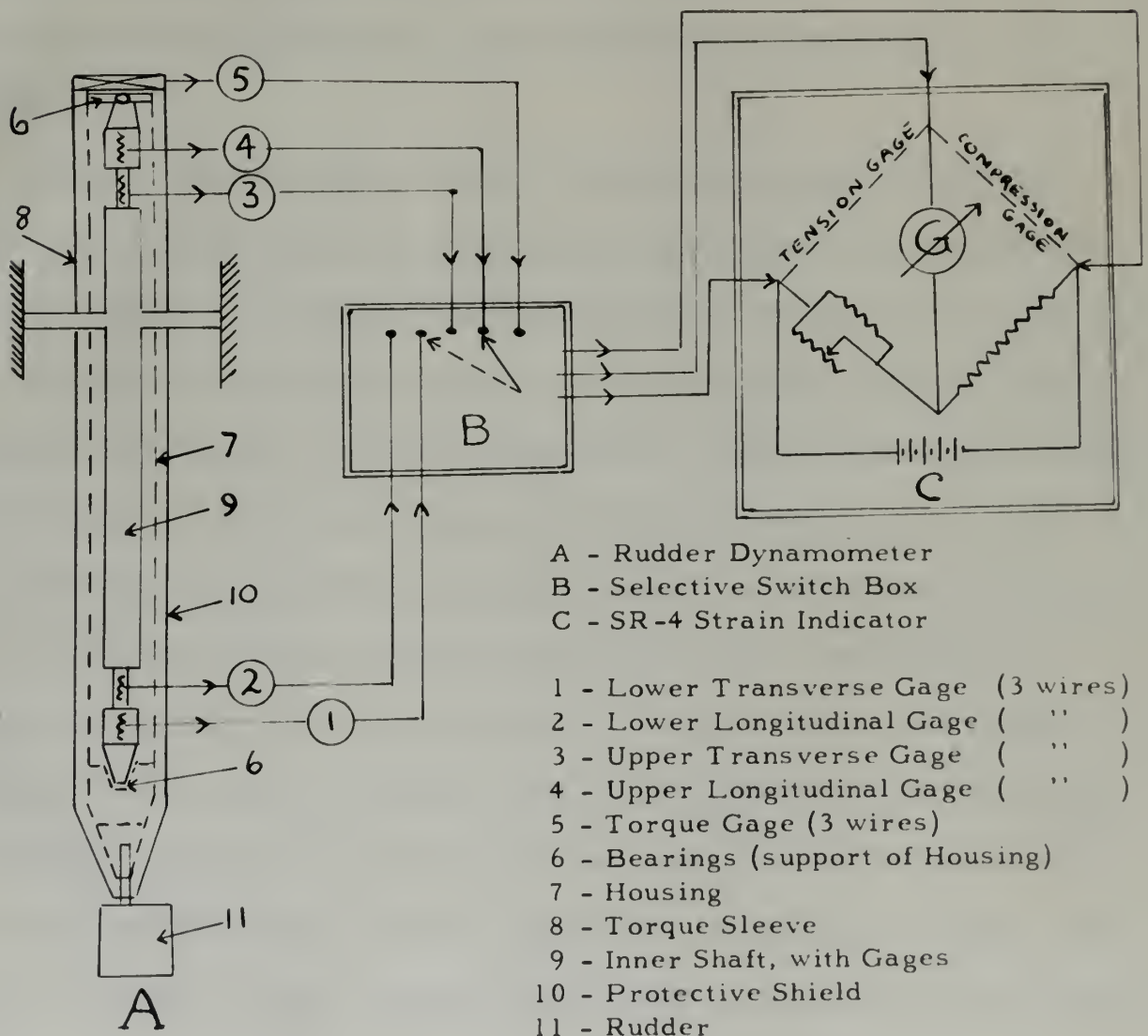
APPENDIX "A"

VIII. APPENDIX

APPENDIX "A"

THE M. I. T. MODEL RUDDER DYNAMOMETER

The measurement of Lift and Drag forces for the development of this thesis was made with the Model Dynamometer designed by Kissinger and Rupp (11). A sketch of the Dynamometer's essential details and a brief explanation of its operation follows:



A - Rudder Dynamometer
B - Selective Switch Box
C - SR-4 Strain Indicator

1 - Lower Transverse Gage (3 wires)
2 - Lower Longitudinal Gage (")
3 - Upper Transverse Gage (")
4 - Upper Longitudinal Gage (")
5 - Torque Gage (3 wires)
6 - Bearings (support of Housing)
7 - Housing
8 - Torque Sleeve
9 - Inner Shaft, with Gages
10 - Protective Shield
11 - Rudder

NOTE: Resistors shown dotted in the Wheatstone Bridge are the pair of gages (tension & compression) in use; they actually are mounted on the dynamometer.

The Model Dynamometer consists of a steel shaft (9) carrying two sets of strain gages (1, 2, 3, 4) and rigidly supported by a casting, which is the only outside support. The four strain gages are mounted in two mutually perpendicular reduced sections at the upper and lower end of the shaft, i.e., parallel and normal to the water flow. The shaft is enclosed by a watertight cylinder (7) which is supported at both ends of the shaft (9). The rudder stock is firmly held by this cylinder, thus transmitting all forces to the inner shaft.

Above the dynamometer support a sleeve (5) is mounted around the cylinder; the torque gage is installed between this sleeve and the cylinder (7). This gage will not be discussed here as it was not used during the experiments.

Below the Dynamometer support there is a protective shield (10) with the lower end tapered. To avoid corrections for drag forces this tapered end was brought very close to the upper surface of the rudder.

The strain gages consist of fine wires cemented to the reduced sections in the direction of the pure bending introduced by either longitudinal or transverse forces. Three electrical leads are used with each strain gage, namely - tension side, compression side and neutral axis (common ground). The leads from all gages were connected to a selective switch box which in turn was connected to the SR-4 Strain Indicator. This indicator consists of a built-in Wheatstone bridge with galvanometer for obtaining balance among the resistances. A high sensitivity, as well as temperature correction, was obtained by connecting simultaneously the tension and compression leads from the gage in use to the SR-4 Indicator.

Due to changes made in the Dynamometer it was decided to use only the two lower strain gages, the location of the upper gages making their readings less sensitive than the lower. During calibration of the Lower Longitudinal Gage, care was taken to insure that only longitudinal forces would act on the Dynamometer (by keeping zero reading on the Transverse Gage). Therefore, the SR-4 Indicator reading for a given longitudinal force was always the same, regardless of the readings of the upper gages. The same applies to the Lower Transverse Gage.

This procedure simplifies the use of the Rudder Dynamometer as it does not require the resolution of the applied load into its upper and lower components, as was required in the original design.

The use of the SR-4 Strain Indicator together with the selective switch simplified considerably the test procedure.

For a detailed explanation of the Rudder Dynamometer the reader is referred to reference (11) in the bibliography.

APPENDIX "B"

CALIBRATION DATA

(Ahead motion) Date: 2/24/1950

Gauge Lower Transverse (LT)		Gauge Lower Longitudinal (LL)	
Applied Load	Strain reading (micro-inches)	Applied Load	Strain reading (micro-inches)
	Left rudder		----------
0#	5960	0#	5850
1	5800	1	6000
2	5630	2	6130
3	5470	3	6280
4	5300	4	6430
5	5140	5	6580
6	4970	6	6715
7	4810	7	6860
8	4640	8	7000
9	4470	9	7145
10	4310	10	7290
11	4140	11	7430
12	3960	12	7585
13	3790	13	7740
14	3630	14	7875
15	3460	15	8020
16	3280	16	8160
17	3115	17	8300
18	2950	18	8450
19	2780	19	8600
20	2620	20	8745
21	2430	21	8900
22	2270	22	9045
23	2100	23	9190
24	1930	24	9340
25	1780	25	9490
		26	9630
	Right Rudder		
1	6150		
2	6310		
3	6480		
4	6640		
5	6810		
6	6960		
7	7120		
8	7280		
9	7440		
10	7610		

CALIBRATION DATA

(Annual meeting)

Date: 4/24/1930

Gauge Lower Transverse (L.T.)

Gauge Lower Longitudinal (L.L.)

Applied Load	Dial reading (before-reading)	Applied Load	Dial reading (before-reading)
	Left rudder		
0	3960	0	5320
1	3800	1	6060
2	8030	2	6130
3	5472	3	8010
4	7300	4	6430
5	2160	5	6320
6	4710	6	6413
7	8510	7	6202
8	9940	8	7008
9	4470	9	7145
10	3310	10	7290
11	4140	11	7139
12	3760	12	7264
13	3790	13	7146
14	3630	14	7027
15	3460	15	6910
16	8320	16	6160
17	3130	17	8300
18	3950	18	6430
19	5780	19	8800
20	5650	20	8134
21	3630	21	6900
22	3670	22	6943
23	3160	23	6168
24	1930	24	6340
25	1780	25	6906
		26	6830

Right rudder

1	5120
2	6310
3	4840
4	6640
5	8810
6	6950
7	7130
8	7280
9	7440
10	7810

The calibration curves (Figure XII) were plotted after obtaining the data from the preceding page and were used throughout the tests, checks being made after each series of runs.

The calibration curves (Figure 3.11) were plotted after obtaining the data from the preceding page and were used (throughout the tests, checks being made also much earlier of them.

SAMPLE LIFT COEFFICIENTS USED ON PLOTS*

Rudder Angle	Rudder 0%	Rudder 10%	Rudder 20%	Rudder 30%	Rudder 40%	Rudder 50%
0°	0.0	0.0	0.0	0.0	0.0	0.0
3	.069	.127	.097		.092	
5	.132	.175	.147	.143	.150	.153
7	.175	.225	.200	.234	.215	
10	.279	.309	.283	.292	.310	.313
13	.360	.393	.362	.387	.378	
15	.429	.475	.446	.441	.466	.450
18	.525	.570	.550	.562	.542	
20	.585	.630	.587	.614	.608	.500
22	.644	.705	.671	.688	.654	
25	.760	.790	.752	.735	.743	.715
28	.847		.850	.804	.837	.770
30	.894	.927	.897	.908	.894	.825
32	.955	.630	.980	.970		.868
33	.953	.605	.991	.998	.880	.532
34	.960			1.021	.994	
35		.715	1.018	1.028	.860	.561

*The above tabulation refers to one series of runs only.

The curves of Figures I to VI were plotted with data of five complete series of runs.

0°	5.0	8.0	5.0	8.0	5.0	8.0
4	.869	.117	.897	.991		
8	.152	.178	.141	.163	.189	.181
12	.379	.414	.390	.434	.412	.439
16	.579	.596	.588	.575	.596	.614
20	.719	.723	.704	.717	.723	.719
24	.819	.813	.844	.806	.801	.809
28	.879	.869	.889	.855	.843	.842
32	.906	.894	.902	.874	.859	.858
36	.944	.908	.871	.865	.834	.824
40	.960	.937	.934	.903	.863	.843
44	.967	.944	.950	.919	.884	.859
48	.974	.951	.957	.929	.894	.869
52	.979	.957	.962	.936	.903	.878
56	.982	.962	.966	.942	.911	.886
60	.986	.966	.969	.947	.918	.894
64	.989	.969	.972	.951	.924	.901
68	.991	.972	.975	.955	.929	.907
72	.993	.975	.978	.959	.934	.913
76	.995	.978	.981	.963	.939	.919
80	.997	.981	.984	.967	.944	.925
84	.999	.984	.987	.971	.949	.931
88	1.000	.987	.990	.975	.954	.937
90	1.000	.988	.991	.977	.957	.940

- The above tabulations refers to one meters of rope only.

The curves of Figures 1 to VI were plotted with data of five consecutive meters of rope.

SAMPLE DRAG COEFFICIENTS USED ON PLOTS*

Rudder Angle	Rudder 0%	Rudder 10%	Rudder 20%	Rudder 30%	Rudder 40%	Rudder 50%
0°	.040	.040	.040	.040	.040	.040
3	.041	.046	.040	.044	.046	. -
5	.046	.051	.050	.050	.051	.045
7	.056	.061	.055	.066	.056	. -
10	.066	.077	.060	.071	.066	.066
13	.071	.102	.071	.081	.076	. -
15	.097	.117	.096	.096	.087	.096
18	.123	.148	.127	.137	.112	. -
20	.153	.194	.142	.158	.143	.142
22	.184	.214	.183	.192	.188	. -
25	.230	.250	.224	.244	.209	.209
28	.301	.327	.285	.290	.273	. -
30	.332	.352	.326	.331	.313	.300
32	.383	.357	.362	.392	.355	.331
33	.408	.455	.377	. -	.369	.392
34	.440	. -	. -	.444	.461	. -
35	.460	.485	.400	.479	.450	.439

(*) The above tabulation refers to one series of runs only; the data was corrected for drag at zero rudder angle to be equal for all rudders.

The curves (Figures I to VI) were plotted with data of five complete series of runs.

Incidence Angle	Incidence (CS)	Incidence (CSP)	Incidence (SSP)	Incidence (SSP)	Incidence (SSP)
0°	.858	.861	.860	.858	.860
1	.861	.866	.864	.862	- -
3	.868	.871	.870	.868	.869
5	.874	.877	.876	.874	- -
10	.894	.897	.896	.894	.895
15	.914	.917	.916	.914	- -
20	.934	.937	.936	.934	.935
25	.954	.957	.956	.954	- -
30	.974	.977	.976	.974	.975
35	.994	.997	.996	.994	- -
40	1.014	1.017	1.016	1.014	1.015
45	1.034	1.037	1.036	1.034	- -
50	1.054	1.057	1.056	1.054	1.055
55	1.074	1.077	1.076	1.074	- -
60	1.094	1.097	1.096	1.094	1.095
65	1.114	1.117	1.116	1.114	- -
70	1.134	1.137	1.136	1.134	1.135
75	1.154	1.157	1.156	1.154	- -
80	1.174	1.177	1.176	1.174	1.175
85	1.194	1.197	1.196	1.194	- -
90	1.214	1.217	1.216	1.214	1.215

(*) These scores tabulation refers to one section of cross only (the data was corrected for skew so that cross section is the equal for all readers.

The curves (Figures 1 to 17) were plotted with data of line centerline

DATA FOR CURVES ON FIGURES IX and X

LIFT COEFFICIENT C_L - vs - RUBBER PERCENTAGE*

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	.132	.167	.152	.146	.148	.152
10°	.283	.310	.298	.293	.295	.302
15°	.433	.467	.450	.445	.445	.450
20°	.593	.620	.602	.595	.599	.560
25°	.760	.797	.775	.748	.739	.701
30°	.898	.925	.915	.890	.865	.833

DRAG COEFFICIENT C_D - vs - RUBBER PERCENTAGE*

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	.045	.051	.049	.047	.047	.047
10°	.065	.075	.070	.068	.064	.064
15°	.095	.110	.107	.103	.097	.095
20°	.155	.165	.160	.152	.145	.138
25°	.232	.251	.242	.226	.210	.193
30°	.330	.348	.340	.325	.310	.292

C_L/C_D - vs - RUBBER PERCENTAGE

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	2.93	3.28	3.10	3.11	3.15	3.24
10°	4.36	4.13	4.26	4.32	4.62	4.72
15°	4.56	4.25	4.21	4.33	4.59	4.74
20°	3.83	3.80	3.76	3.92	4.13	4.20
25°	3.28	3.18	3.20	3.31	3.52	3.63
30°	2.72	2.66	2.69	2.74	2.79	2.85

*NOTE: These values were taken from faired curves on Figures VII and VIII.

APPENDIX "C"

APPENDIX "C"

TYPICAL DATA SHEET

Rudder: 0% rubber

Water temperature: 62°F - Water speed: 9 ft/sec. - Date: 3/24/50

Rudder Angle (right)	Gauge LT Reading	Lift Force	C_L	Gauge LL Reading	Drag Force	C_D
0°	5960	0.0	0.000	5960	0.8	.041
3	5725	1.4	.071	5960	0.8	.041
5	5580	2.3	.117	5970	0.9	.046
7	5350	3.5	.179	5980	1.1	.056
10	5035	5.6	.286	6030	1.3	.068
13	4770	7.1	.362	6050	1.4	.071
15	4530	8.6	.440	6110	1.9	.097
18	4250	10.3	.526	6180	2.4	.123
20	4010	11.7	.596	6260	3.0	.153
22	3750	13.2	.675	6360	3.6	.184
25	3450	15.0	.766	6490	4.5	.230
28	3180	16.6	.848	6670	5.9	.301
30	3030	17.5	.895	6780	6.5	.332
32	2830	18.7	.955	6930	7.5	.383
33	2710	19.4	.990	7000	8.0	.408
34	2650	19.7	1.005	7090	8.6	.440
(left) 5°	6475	3.0	.153	5985	1.0	.051
8	6760	4.8	.245	6020	1.2	.061
10	6960	6.0	.306	6060	1.5	.076

TUNNEL DATA SHEET

Runway 09 Number

Valve Temperature: 132°F - Water speed: 3 ft/sec. - Time: 3/19/76

Rudder Angle (Right) δ_r	Change L.F Reading	L.E Force	C_n	Change L.C Reading	Drag Force	C_D
	9900	0.0	0.000	9990	0.0	.000
5	9723	1.4	.011	9949	0.4	.001
9	9599	3.3	.117	9910	0.9	.011
7	9410	3.3	.179	9930	1.1	.020
10	9021	5.9	.239	9919	1.3	.024
13	8178	7.1	.281	9929	1.4	.031
15	8550	8.4	.289	9110	1.4	.032
16	8250	10.3	.374	9190	3.4	.113
19	7618	11.1	.398	9258	3.0	.123
22	7170	13.3	.474	9300	3.8	.134
23	7450	13.8	.490	9403	4.3	.130
23	7170	15.3	.544	9486	5.9	.191
28	7020	17.3	.601	9590	6.5	.221
31	6350	17.7	.623	9730	7.3	.263
34	5710	19.4	.668	9900	8.0	.305
36	5450	19.7	1.003	9990	9.4	.340
α_w (Deg)	5612	3.0	.122	9982	1.0	.021
2	6750	5.8	.344	9950	1.2	.041
12	6960	6.0	.346	9960	1.5	.019

SAMPLE CALCULATION

From "Sample Data Sheet" on page 45, for 20° right rudder,

Lift Force = 11.7 lbs.

Drag Force = 3.0 lbs.

Water density (at 62° F) = ρ = 1.9379 $\frac{lb.sec^2}{ft^4}$

Rudder area = S = 0.25 ft^2

Water speed = V = 9.0 ft/sec.

$$\text{Lift Coefficient} = C_L = \frac{F_L}{1/2 \rho S V^2} = \frac{11.7}{1/2(1.9379)(0.25)(81)} = 0.596$$

$$\text{Drag Coefficient} = C_D = \frac{F_D}{1/2 \rho S V^2} = \frac{3.0}{1/2(1.9379)(0.25)(81)} = 0.153$$

APPENDIX "D"

ORIGINAL DATA

The original data is in the custody of Professor S. Curtiss Powell.

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APPENDIX "E"

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